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DEPLETION OF INTERSTELLAR SODIUM AND CALCIUM

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ABSTRACT

New measurements of the Ca II/Ca I ratios in interstellar clouds lead to the conclusion that not only Ca, but also Na, is underabundant in these regions. Recent calculations of element depletion by accretion of atoms onto dust grains probably cannot account for the observed abundance range. The extreme underabundance of Ca, and some part of the abundance range, probably reflects the composition of the grain cores.

Subject headings: abundances — interstellar matter

I. INTRODUCTION

Determinations of interstellar Na and Ca abundances from observations of the Na I and Ca II optical absorption lines use the condition of ionization equilibrium to estimate the relative concentration of atoms in unobservable ionization states, and the derived abundances depend sensitively on the electron density adopted in the ionization equilibrium. Measurements of Ca II/Ca I ratios (Hobbs 1971; White 1973) now provide an observational estimate of the mean electron density in interstellar clouds (White 1973), which makes possible a reexamination of the Na and Ca abundances and leads to the conclusion that Na, as well as Ca, is significantly underabundant.

II. THE Na AND Ca ABUNDANCES

In deriving the abundances we assume that all the Na I and Ca II interstellar lines arise in regions having similar physical conditions, as characterized by the Ca II/Ca I ratio. The validity of this assumption is quite well established for the majority of the observed lines, which have low velocities relative to the local standard of rest, $|v_{\rm LSR}| \leqslant 10$ km s^{-1}, show a high correlation with 21-cm velocity components (Howard, Wentzel, and McGee 1963), and arise predominantly, if not exclusively, in cool ($T \leqslant 100°$ K) interstellar clouds (Hobbs and Zuckerman 1972; White 1973). However, the optical lines at $(v_{\rm LSR}| \gtrsim 10$ km s^{-1} characteristically differ from the majority: they are generally weaker, exhibit larger Ca II/Na I ratios (Routly and Spitzer 1952), and usually lack a corresponding 21-cm velocity component (Goldstein and MacDonald 1969; Habing 1969). Although Ca I absorption from these "high-velocity clouds"[1] has not been detected the assumption of a uniform Ca II/Ca I ratio is consistent with the data. Also one may argue on other grounds that the high-velocity clouds probably are cool H I clouds. First, they are kinematically similar to, and in several cases identical with intermediate-velocity clouds found in 21-cm surveys (Habing 1969; Rickard 1972), and at least one intermediate-velocity cloud is known to be cool (Verschuur 1969). Second, the frequent occurrence of optical lines without a 21-cm counterpart ("noncoincident" lines) can be simply explained by beam dilution if the high-velocity clouds are cool H I regions, while other explanations for these lines encounter serious difficulties. Specifically, the hypothesis that the noncoincident lines originate in H II regions cannot simply explain the observed velocities (Habing 1969) and is contradicted in at least one case by the width of the observed Na I lines (ρ Leo, Hobbs 1969); and the hypothesis that they arise in intercloud H I regions ($T \simeq 10^3$ ° K) cannot account for the strength of the Na I lines in the absence of 21-cm emission without postulating that the Na abundance exceeds the cosmic value. We therefore proceed under the assumption that all the observed Na I and Ca II lines originate in interstellar clouds having $T \leqslant 100°$ K.

At low temperatures ionization equilibrium is established for Ca and Na in a time short compared to the cloud lifetime. Consequently if a small contribution from Ca I is neglected the abundance of Ca relative to hydrogen is related to the observed column

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[1] We adopt the nomenclature of Routly and Spitzer (1952). The "high-velocity clouds" discussed here should not be confused with the "high-velocity clouds" discussed by 21-cm observers (e.g., Meng and Kraus 1970), which have $|v_{\rm LSR}| \gtrsim 80$ km s^{-1}.

density ratio [Ca II/H I] by the equation

$$\left[\frac{\mathrm{Ca}}{\mathrm{H}}\right] = \left[\frac{\mathrm{Ca\,II}}{\mathrm{H\,I}}\right]\left[\frac{\mathrm{H\,I}}{\mathrm{H}}\right]\left\{1 + \left[\frac{\mathrm{Ca\,III}}{\mathrm{Ca\,II}}\right]\right\}$$

$$= \left[\frac{\mathrm{Ca\,II}}{\mathrm{H\,I}}\right]\left[\frac{\mathrm{H\,I}}{\mathrm{H}}\right]\left[1 + \frac{\Gamma(\mathrm{Ca\,II})}{\alpha(\mathrm{Ca\,II})n_e}\right], \quad (1)$$

where Γ is the photoionization rate, α is the recombination coefficient and n_e is the electron density, which may be eliminated by consideration of the Ca I–Ca II ionization equilibrium, yielding

$$\left[\frac{\mathrm{Ca}}{\mathrm{H}}\right] = \left[\frac{\mathrm{Ca\,II}}{\mathrm{H\,I}}\right]\left[\frac{\mathrm{H\,I}}{\mathrm{H}}\right] \times \left\{1 + \left[\frac{\mathrm{Ca\,II}}{\mathrm{Ca\,I}}\right]\left[\frac{\Gamma(\mathrm{Ca\,II})}{\Gamma(\mathrm{Ca\,I})}\right]\left[\frac{\alpha(\mathrm{Ca\,I})}{\alpha(\mathrm{Ca\,II})}\right]\right\}. \quad (2)$$

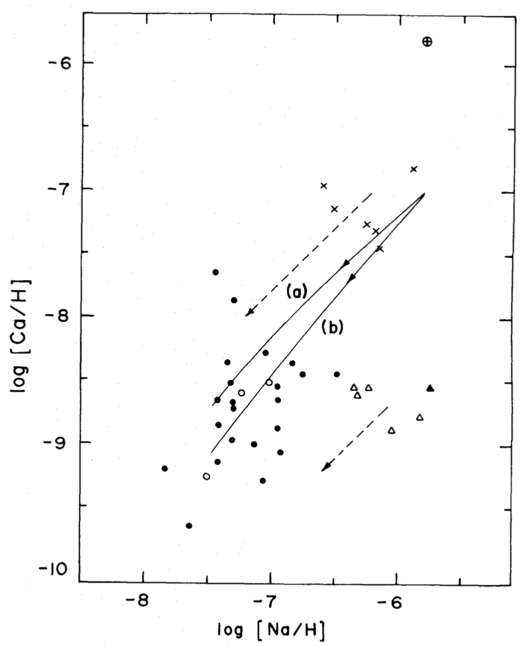

FIG. 1.—Ca and Na abundances in interstellar clouds. $\otimes$ cosmic abundances. *Crosses*, clouds having noncoincident Ca II and Na lines; *triangles*, clouds having strong coincident lines, N(Na I) determined from D-lines; *circles*, other clouds having coincident lines, N(Na I) determined from D-lines. The open triangles and circles represent clouds for which [Ca II/Ca I] has been measured. The dashed arrows indicate the displacement of the triangles and crosses if larger values of N(H I) are adopted. The solid curve (a) is the theoretical depletion law if Γ(Ca II) $= 2 \times 10^{-12}$ s^{-1} for arbitrary initial abundances [Na/H] $= 1.6 \times 10^{-6}$, [Ca/H] $= 1 \times 10^{-7}$. Curve (b) is the theoretical curve if Γ(Ca II) $= 2 \times 10^{-11}$ s^{-1}.

TABLE 1

IONIZATION RATES AND RECOMBINATION COEFFICIENTS

Ion	Γ* (s^{-1})	$(T/100)^{0.7}\alpha$† ($cm^3\ s^{-1}$)
Na I......	2×10^{-11}	5.9×10^{-12}
Ca I......	2×10^{-10}	6.0×10^{-12}
Ca II	2×10^{-12}	3.5×10^{-11}

* For the ionization cross-sections cited by Herbig (1968) and the radiation field of Witt and Johnson (1972).

† Seaton (1951).

A similar equation relates [Na/H] to [Na I/H I] when ionization of Na I by charge exchange with C II is neglected (Solomon and Klemperer 1972; this process might increase the derived [Na/H] by a factor of 1.2 for $u_{\mathrm{H}} \simeq 10$ or a factor of 3 for $n_{\mathrm{H}} \simeq 10^2$ if [C/H] is normal). Because the abundances depend on ratios of the ionization and recombination coefficients, they are independent of temperature and insensitive to local variations in the flux of ionizing radiation.

Figure 1 presents the abundances found for the interstellar line components listed by Pottasch (1972 *b*) using the values of Γ and α given in table 1 and either the observed [Ca II/Ca I] (Hobbs 1971; Pottasch 1972*a*; White 1973; *open symbols*) or a representative value, 250 (White 1973; *filled symbols and crosses*). The lack of systematic difference between the positions of the open and filled circles in figure 1 supports the assumption of uniform Ca II/Ca I ratios among the low-velocity clouds.

The clouds represented by circles in figure 1 typically have Na/H $\simeq 7 \times 10^{-8}$ and Ca/H $\simeq 2 \times 10^{-9}$, respectively 20 and 800 times smaller than the cosmic abundance ratios (Allen 1963). The underabundances exceed the possible systematic errors in the analysis, perhaps a factor of ~ 6 for Na and ~ 15 for Ca which might be caused by overestimates of the cosmic abundances, neglect of charge exchange ionization of Na I, and underestimate of Γ(Ca II), which is subject to substantial uncertainty (Brown 1972). Like previous investigators (Howard *et al.* 1963; Habing 1969; Savage and Jenkins 1972), we therefore find that Ca is grossly underabundant; but, unlike them, we also find that Na is underabundant by more than an order of magnitude. The decreased abundances effectively result from the use of larger electron densities in equation (1), and were anticipated on theoretical grounds by Habing and Pottasch (1967).

The region occupied by the circles in figure 1 is limited primarily by observational selection, and the clouds with strong Na lines [which have N(Na I) determined from λ3302; *triangles*] and the high-velocity clouds with noncoincident optical lines (*crosses*) suggest that the abundance range may be very large. Unfortunately, the abundances in both groups of clouds are still quite uncertain. For the strong-lined clouds there is evidence that N(H) may have been underestimated [compare Savage and Jenkins (1972) and Carruthers (1970) with Pottasch (1972*b*)]; and there is a possibility (Sinanoğlu, private communication) that N(Na I) has been overestimated due to an error in the λ3302 oscillator strength, even though this seems unlikely in view of the good agreement between theoretical and experimental f-values (Weisheit and Dalgarno 1971; Schmieder *et al.* 1970). These uncertainties can probably be removed by rocket or satellite measurements of H I and H_2 absorption and by the detection of the λ3302 lines in stars for which a reliable determination of N(Na I) can be made from the D-lines. For the clouds having noncoincident optical lines, N(H I) is unknown. To plot the crosses in figure 1, we took N(H I) equal to the upper limit given by Pottasch (1972*b*); but, as indicated by the broken arrow in the figure, the value might be substantially larger if beam dilution is important.[2] Independent of this uncertainty, figure 1 suggests that the high-velocity clouds have significantly larger [Ca/H] than the low velocity clouds. A more reliable determination of the abundances awaits very sensitive 21-cm observations of these objects with high angular resolution.

III. DISCUSSION

The idea that interstellar element abundances are decreased by accretion of atoms onto dust grains, first discussed by Routly and Spitzer (1952), has recently received considerable attention because of its implications for the cooling of the interstellar gas (Field, Goldsmith, and Habing 1969). The accretion calculations (Mészáros 1972; Aannestad 1973) make the customary assumption that the depletion rate for an ion is proportional to the frequency of its collisions with dust grains. For the calculated temperatures and electron densities and Γ(Ca II) from table 1, most Ca atoms are singly ionized, not doubly ionized as usually assumed in the past. So Ca and Na accrete onto the grains at nearly equal rates, giving the "evolutionary track" (a) in figure 1, which is traversed by an isolated cloud in a few times 10^7 years. Such an abundance evolution is clearly inadequate to explain the observed range of Ca abundances. If Γ(Ca II) is 10 times larger than assumed here, the resulting evolutionary track (b) might just be consistent with the observations, but only if the Na abundance has been underestimated in the high-velocity clouds, possibly due to significant charge-exchange ionization or underestimate of [Ca II/Ca I], and greatly overestimated in the strong-lined clouds. Unless both these conditions are fulfilled, one must conclude that accretion processes in the interstellar gas cannot account for the observed range of Ca and Na abundances.

The extreme depletion of Ca from the interstellar gas could not in any case be attributed entirely to accretion. The most likely explanation is that the majority of the Ca atoms are chemically bound in the grain cores. One may expect, then, that the small fraction of gas-phase Ca is initially variable, and is further decreased by accretion processes in interstellar clouds. The high-velocity clouds are most interesting in this regard since their relatively large Ca abundance suggests that they are objects so recently condensed from the intercloud medium that accretion processes have had little effect (Goldsmith, Habing, and Field 1969). If this is correct, they indirectly indicate the fraction of Ca and Na in the grain cores. Figure 1 suggests that this fraction exceeds 90 percent for Ca, possibly approaching 100 percent, and may be as large as 90 percent for Na. These abundances must remain very uncertain until N(H) is determined for the high-velocity clouds. However, intercloud abundances might be measured directly if the expected weak ($\lesssim 1$ mÅ) Ca II and Na I lines can be detected in the spectra of nearby stars for which Lα absorption has been measured (Savage and Jenkins 1972; Rogerson *et al.* 1973).

IV. CONCLUSIONS

The observed Ca II/Ca I ratio in low-velocity interstellar clouds implies that the abundances of Na and Ca are substantially lower than previously believed. The newly derived Na abundance is $\sim$10 times smaller than the cosmic value and the derived Ca abundance is so far below the cosmic value that no plausible change in the uncertain Ca II ionization rate could lead to the derivation of a normal abundance. The total range of Ca and Na abundances, however, is still obscured by observational selection and observational uncertainties about the high-velocity clouds and the strong-lined clouds; these objects deserve further attention.

The recent calculations of element depletion by accretion of atoms onto dust grains by Mészáros (1972) and Aannestad (1973) probably cannot account for the total range of abundances. The extreme depletion of Ca and wide abundance range can probably be explained if a large but variable fraction of the Ca atoms are locked up in the grain cores. The abundances in the high-velocity clouds may reflect the grain core composition but are still very uncertain.

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[2] In this context it is interesting to note that the filled circle indicating the largest [Ca/H] represents a cloud which has $v_{LSR} = 20$ km s^{-1} and barely detectable 21-cm emission.

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